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A Candidate Coaxial Ferrite Phase Shifter for the 8 GeV Linac

- The 8 GeV linac has 400 superconducting cavities.
- An RF system with one Klystron per cavity would require 400 Klystrons. I will not be party to such a design.
- Therefore it must use a "TESLA-style" RF fanout in which many SC cavities (8~10) are fed from a single high-power Klystron. This brings the Klystron count down to the 40-50 range. Thirty of these are "TESLA"-style 1.2GHz, the rest are 805MHz.
- This system loses the flexibility of a one-cavity-per Klystron system to individually control the cavity drive.
- In addition, it is desired to accelerate electrons at ~10 Hz, inbetween the H- injections into the FMI which occur every 1.5 seconds.
  - This requires phase jumps of up to +/-180 degrees between electron and H-/Proton cycles on individual cavity drives
- This phase adjustment must necessarily occur on the high-level cavity feeds, with peak power ~0.5 MW, average power ~60kW.
  - Such a design was started by the SNS, but dropped due to lack of R&D time.
- The speed at which the phase jump takes place is not yet well defined.
  - A minimum requirement is to jump the phase in 0.1 second (between Linac pulses).
  - A ambitious requirement is to use the phase shifters to compensate for phase shifts due to microphonics in the cavities. This may be unnecessary if the microphonics of the final system are small and the piezo tuners work for Lorentz detuning. The present guess is that a response time of ~20-50 usec and a slew rate of ~1 degree/usec would suffice.
- The amplitude control function is also not yet well defined
  - The combination of individual phase shifters, piezo and mechnical tuners, and fast Klystron RF amplitude control will suffice
  - In any case a fast phase shifter can be used to produce fast amplitude control using hybrids, etc. if needed.

KEY SPECIFICATIONS

- 500kW Peak power, 60kW average power.
- 1.2 msec * 10 Hz = 1.2% RF duty cycle
- 360 degree phase adjustment , (~400 degrees if used for feedback)
- Insertion loss ~0.2 dB, corresponding to ~300W of average RF power dissipation
- VSWR of <1.3 over range of phase adjustment. (Reflected power does not cause a problem; it mostly ends up in the back-termination of the directional coupler used for power fanout. It is just an efficiency consideration).

AN EXISTANCE PROOF (AND MAYBE A CANDIDATE FOR THE FINAL DEVICE)

- Developed at Bell Labs circa 1965 for phased-array radar systems
- > 500 degrees of phase adjustment at 1.3 GHz for 60cm length.
- Coaxial design 60cm long. This is compact and might integrate well with the coaxial power coupler to the cavity.
- 0.2 dB insertion loss measured. There are arguments that coax shifters should have lower losses due to better field geometry.
- Power handling up to 350 kW, limited by available power. Scaling a coax design to higher power should be straightforward.
- Ferrite is biased above resonance (800-1500 Oe) so a substantial biasing coil is required.
- Bias coil power dissipation 2kW DC, which translates to ~30 W for pulsed operation at (2msec*10Hz)=2% duty cycle

The following pages are excerpted from:
Von Aulock and Fay, "Linear Ferrites for Microwave Applications", Academic Press, 1968, p.174-83

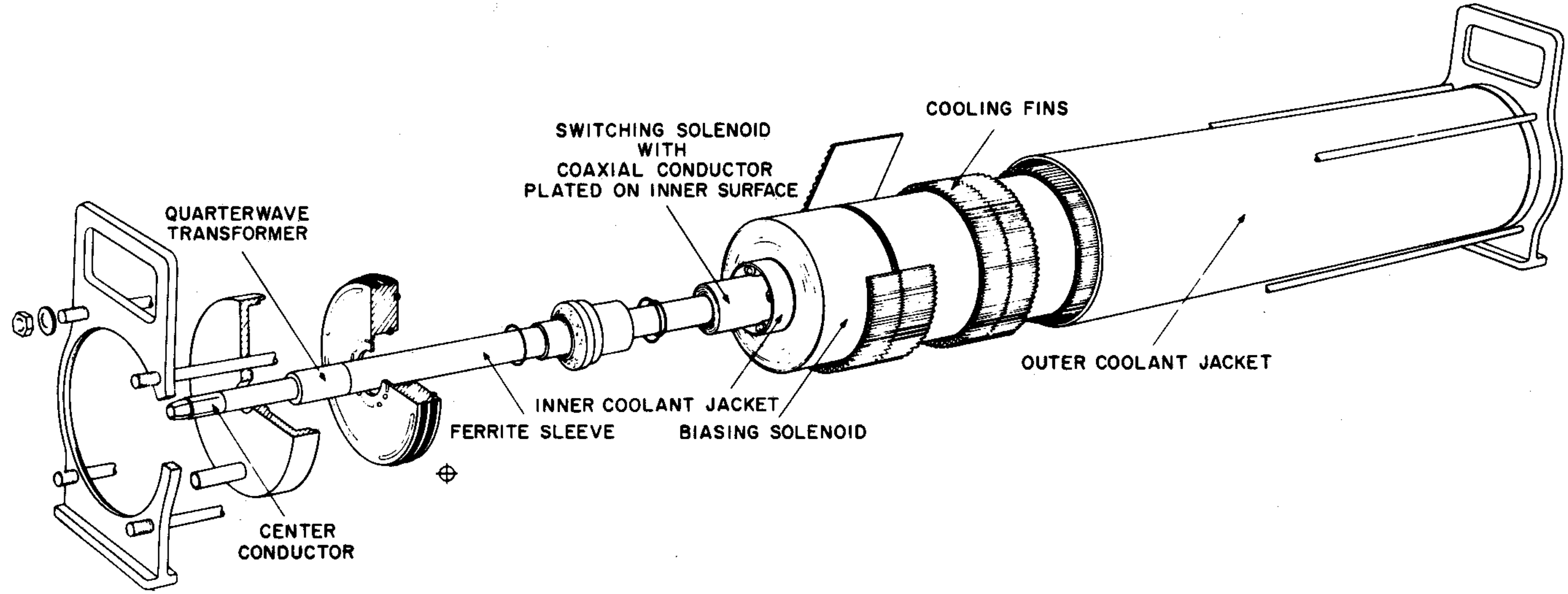

FIG. 129. ***L*-band coaxial phase shifter for high-power applications.**

b. *A Coaxial Phase Shifter for Operation above Resonance.* At low frequencies, between 1 and 2 GHz, operation above resonance becomes practical (*81*) and below 1 GHz it is necessary (*82*). Figure 129 shows an above-resonance phase shifter for 1.2 to 1.4 GHz and for rf peak power levels above 350 kW. A 3/8- to 7/8-in (9.5 to 22.5 mm) coaxial line is completely filled with a 24-in (61 cm) Mg, Mn, Al-ferrite sleeve with a saturation magnetization of 700 Oe. Two biasing coils produce a variable field of 350 Oe for phase shifting and a constant field of 1025 to 1150 Oe for biasing of the ferrite above resonance. These coils are wound from aluminum foil to improve heat conduction. An elaborate cooling system consisting of inner and outer jackets removes the heat which is dissipated in the coils and in the ferrite. Here again the outer conductor is made of silver-plated plastic to reduce eddy current losses from switching transients. The phase shift characteristic of this device for three frequencies is shown on Fig. 130.

Plots of relative figure of merit vs. applied field (Fig. 131) demonstrate how closely resonance can be approached before F_m deteriorates. At room temperatures F_m reaches a maximum at 800 Oe ($\sigma = 1.7$), whereas at elevated temperatures the maximum moves down to 640 Oe ($\sigma = 1.4$). The reason for this very desirable shift to lower biasing fields is a decrease in magnetic loss with increasing temperature caused by a reduction of saturation magnetization and a narrowing of the resonance linewidth.

Insertion loss of this phase shifter was very low (about 0.2 dB) and ferrite breakdown due to high-power effects was not observed, even for the highest available peak-power levels (350 kW). However, from a practical point of view, it should be noted that the device weighed 110 lb and used more than 2 kW of control power.

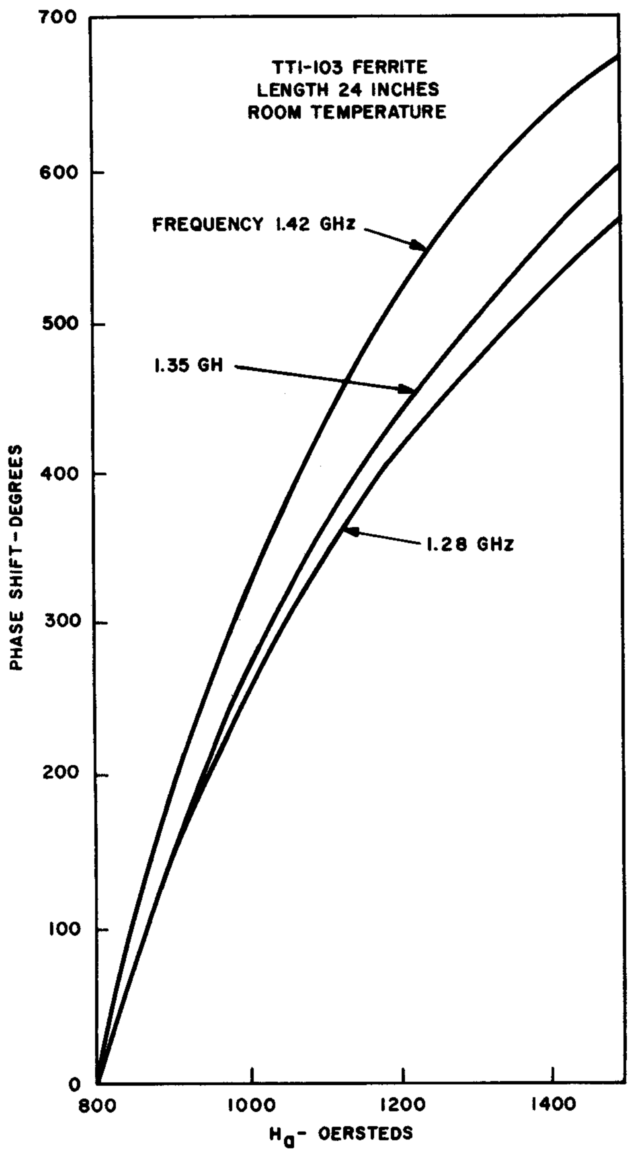

FIG. 130. Frequency dependence of phase shift vs. field for *L*-band phase shifter. (Ferrite length, 61 cm.)

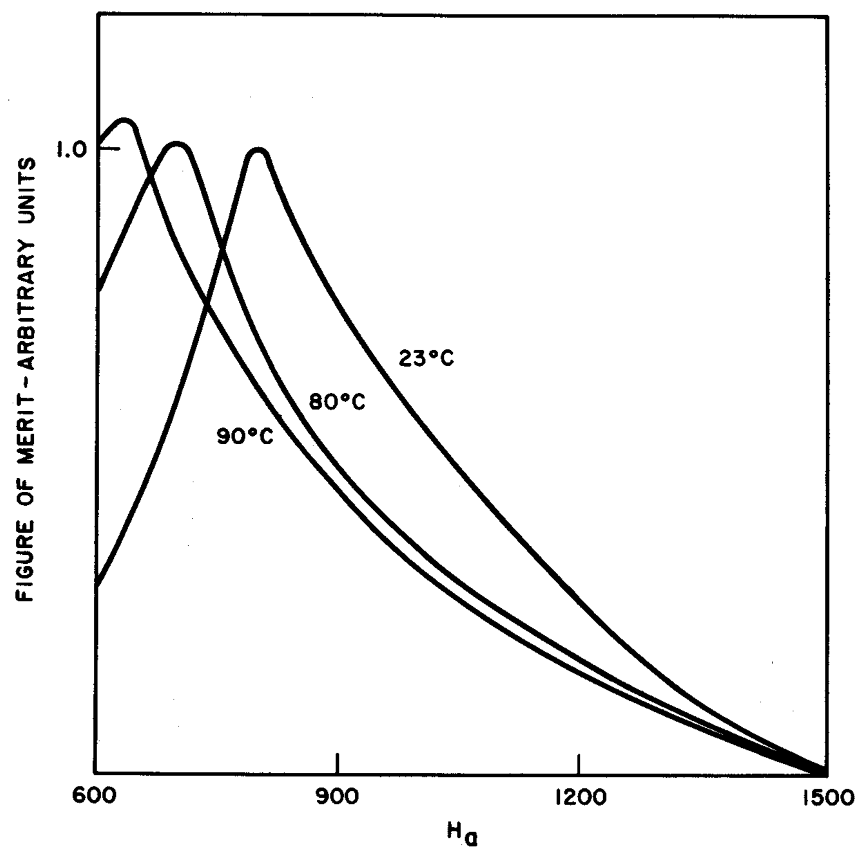

FIG. 131. Effect of temperature on figure of merit vs. applied dc field for *L*-band coaxial phase shifter.

A. Phase Shifters with Longitudinal Biasing Field

Analysis of ferrite devices with longitudinal biasing field (Chapter III, Section C) suggests two reciprocal phase shifter geometries: the TEM-limit mode device consisting of a parallel-plate or coaxial transmission line completely filled with ferrite, and the relatively thick ferrite rod in air excited with a linearly polarized wave. The latter device needs a waveguide enclosure to couple energy into and out of the ferrite rod. This phase shifter was first proposed by Reggia and Spencer (*18*) and gained immediate popularity because of its high F_m and low biasing fields. Both devices complement each other in some respects. The coaxial phase shifter is restricted to the low end of the microwave frequency band, whereas the Reggia–Spencer phase shifter works best at frequencies above 3 GHz up to 35 GHz.

1. The Coaxial Phase Shifter

The complex propagation constant of a completely ferrite-filled coaxial line with longitudinal biasing field (Fig. 11) is given to good approximation by (28).

$$\beta = \omega(\varepsilon_0 \varepsilon\mu_0 \mu_e)^{1/2} \tag{180}$$

$$\Gamma' = (\varepsilon'\mu_e')^{1/2}$$

$$\Gamma'' = \frac{1}{2}\left(\frac{\varepsilon''}{\varepsilon'} + \frac{\mu_e''}{\mu_e'}\right)\Gamma'$$

Phase shift is produced by changing the effective permeability μ_e through a variable biasing field. From analysis of μ_e (7), (8) and from the discussion of the coaxial switch (Chapter VI, Section A,2), it is clear that there are two regions for phase-shifter operation, below cutoff ($\sigma < 1 - p$) and above resonance [$\sigma > (1 - p^2/4)^{1/2} - p/2$]. The cutoff region (163) is forbidden.

The phase shift is negative because μ_e' decreases with increasing biasing field. It can be computed readily from (180) and (174).

$$\Delta\psi = \frac{2\pi l}{\lambda_0}[\varepsilon'\mu_e'(m)]^{1/2}\left[1 - \left(\frac{\mu_e'(0)}{\mu_e'(m)}\right)^{1/2}\right] \tag{181}$$

The figure of merit can be estimated from (177) by noting that in the low-loss region of operation

$$C_L = \frac{1}{2}\left(\frac{\varepsilon''}{\varepsilon'} + \frac{\mu_e''(m)}{\mu_e'(m)}\right) \tag{182}$$

Combining (177), (178), and (182) and neglecting dielectric loss in the ferrite, we obtain

$$F_m = 26.4(S - 1)\frac{\mu_e'(m)}{\mu_e''(m)} \quad \text{(degree/dB)} \tag{183}$$

where (m) refers to the condition of maximum loss in the operating region.

The quantity μ_e'/μ_e'' was called Q_μ in the discussion of Y-junction circulators (138). It may be as high as $Q_\mu = 100$ for narrow linewidth materials. However, it is difficult to design a phase shifter where Q_μ stays high over the entire operating region. Hence, values of F_m can be expected to decrease as phase shift per unit length and VSWR increase.

The frequency variation of phase shift depends on the region of operation. Below resonance, phase shift decreases with frequency whereas it increases above resonance. This can be demonstrated qualitatively as follows. Consider a device which is operated in the unsaturated region. We have $\mu_e(0) \approx 1$ for zero biasing field, and $\mu_e(m) = 1 - p^2$ at saturation. The phase shift can be written as

$$\frac{\Delta\psi}{l} = \omega(\varepsilon_0 \varepsilon\mu_0)^{1/2}[1 - (1 - p^2)^{1/2}]$$

For small $p = |\gamma| M_s/\omega$, the phase shift is proportional to $1/\omega$. Well above resonance, the effective permeability can be approximated by

$$\mu_e \approx 1 + \frac{p}{\sigma} \qquad (\sigma \gg 1) \tag{184}$$

This quantity is independent of frequency to the order of the approximation. Consequently the phase shift is proportional to frequency and the device has the characteristics of a variable delay line.

Suppression of higher-order modes is accomplished by adjusting the mean circumference of the coaxial line (Fig. 11) such that $2\pi r_0 < \lambda_0/(\varepsilon\mu_e)^{1/2}$ and the spacing $2a$ is such that $2a < \lambda_0/2(\varepsilon\mu_e)^{1/2}$.

Operation below resonance requires selection of a material with a relatively low M_s ($p \ll 1$) to permit saturation of material before cutoff is reached at $\sigma_c = 1 - p$. To insure low loss and a high figure of merit, loss must be low over the entire region of biasing fields. This implies absence of increased low field loss (Chapter II, Section A) and narrow line width of the material. Operation above resonance can be attained with a wide range of saturation magnetizations. Values of $p > 1$ are permissible.